

**MEASURING THE INTERNAL STRUCTURE AND PHYSICAL CONDITIONS IN
STAR AND PLANET FORMING CLOUDS CORES: TOWARD A QUANTITATIVE
DESCRIPTION OF CLOUD EVOLUTION**

NAG5-13041

Annual Report No. 2

For the Period 1 April 2004 through 31 March 2005

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January 2005

Prepared for

**National Aeronautics and Space Administration
Goddard Space Flight Center, Greenbelt, MD**

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**The Smithsonian Astrophysical Observatory
is a member of the
Harvard-Smithsonian Center for Astrophysics**

ANNUAL REPORT NASA GRANT NAG5-13041

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Measuring the Internal Structure and Physical Conditions in Star and Planet Forming Cloud Cores: Toward a Quantitative Description of Cloud Evolution

This grant funds a research program to use infrared extinction measurements to probe the detailed structure of dark molecular cloud cores and investigate the physical conditions which give rise to star and planet formation. The goals of this program are to acquire, reduce and analyze deep infrared and molecular-line observations of a carefully selected sample of nearby dark clouds in order to determine the detailed initial conditions for star formation from quantitative measurements of the internal structure of starless cloud cores and to quantitatively investigate the evolution of such structure through the star and planet formation process. During the second year of this grant progress toward these goals was met as follows:

1)- The reduction and analysis of deep NNT and VLT infrared imaging observations of the Lupus 3 cloud were completed. We succeeded in being able to resolve a handful of individual cores within the cloud with our extinction measurements.(see Figure 1.) As a result we were able to examine the structure of these individual cores to a sufficient degree to enable direct comparison with results we have obtained previously for isolated globules such as B68, B335 and the Coalsack. In particular we have measured the radial density profiles of each core and have found them to vary in shape from cores with relatively shallow density profiles to cores with relatively steep density profiles. We also have been able to use Bonnor-Ebert analysis to determine physical parameters of the cores, such as the central core density and the value of the center-to-edge density contrast. By determining both the stability and the degree of star formation activity in each core and comparing this with the cores' density structure we found that the evolutionary state of a core is related to its center-to-edge density contrast, with star formation occurring in the cores with the highest values of this quantity. This is similar to what we found for isolated globules and indicates that the internal structure of a cloud is a measure of its evolutionary state. Moreover this also suggests that the physical parameters we derive for starless cores may be indicative of the initial conditions for star and planet formation. However our results also indicate that the internal structure of a core, as measured by its center-to-edge density contrast, is also correlated with core mass in this cloud. This suggests that star formation and core evolution proceed most rapidly for the most massive cores. This leaves open the question of whether the low mass starless cores will ultimately evolve to form stars or remain relatively stable until disrupted by the star formation in the cloud. A paper describing these results was prepared and submitted for publication to the Astrophysical Journal.

2)- During the reporting period we began reduction and analysis of our deep MMT infrared imaging observations of the IC 5146 cloud in Cygnus. This cloud is the northern hemisphere analog of the Lupus 3 cloud. The analysis is still in progress and will continue into the last year of this proposal. We also continued our investigation of the FES 457 globule in the Pipe nebula. Our millimeter-wave observations with the IRAM 30 meter telescope indicate that this cloud is in a state of global expansion, yet there is no star formation yet identified in the cloud. We have been exploring the idea that this cloud is in a state of oscillation similar to B68 but with only the lowest mode of oscillation present. We also have found strong evidence for depletion of CO and particularly N₂H⁺ in the center of this cloud and are currently investigating the implications of this result. We also obtained

new millimeter-wave molecular-line observations of a number of other globules with the 12 meter telescope of the Arizona Radio Observatories as part of our program to understand the dynamics of these dense objects. In one globule we found intriguing evidence for non-radial oscillations with similar nodal structure to those we uncovered in B68, except in the opposite phase! We have been granted "A" time on the 30 meter IRAM telescope to confirm these results. If confirmed, in this second object, these observations would provide compelling evidence that at least some cores and globules are in a state of dynamical equilibrium and experiencing oscillatory behavior induced by external perturbations. The IRAM observations will be carried out in May and analyzed during the third year of this proposal. Our ARO molecular-line survey also discovered a second starless globule whose outer layers are in a state of global expansion similar to FST 457. Analysis of these data will continue into the next year.

3)- During this period we also finished the data reduction and have nearly completed the analysis of our infrared extinction survey of selected Bok globules. Over the last year this project consisted of three phases: 1) Completing accurate photometry of the stars on the ~50 independent final images and producing final multi-color catalogs for each target globule; 2) The conversion of these infrared catalogs into dust extinction maps using the Near Infrared Color Excess (NICE) method; and 3) Using these dust extinction maps to derive basic physical parameters of the Bok Globules, including masses, and to analyze the density structure of them and determine their evolutionary status.; The first two of these phases of this project have been completed; the third is nearly complete with a summary paper to be submitted to the Astrophysical Journal during Q1 of 2005. We have now produced extinction maps based on a uniform set of deep NNT observations of 14 isolated globules and have examined the internal structure of each one. We have assembled an atlas of extinction maps, star count maps, and radial profiles for the surveyed globules. Figure 2 shows a sample page of the atlas. The upper left panel is the extinction map derived from infrared observations of one of the sources in our survey. The upper right panel is the infrared star count map and the lower right panel displays the radial profile of the cloud calculated from (circular) azimuthal averages of the extinction around the location of peak extinction in the map. Also plotted are various theoretical (Bonnor-Ebert) fits to the density profile. The lower left hand panel is a sigma-A_v plot, which is a metric we use for investigating small scale spatial structure in the cloud. The sigma-A_v plots showed that for all the globules we observed the dispersion was dominated by photometric noise, indicating that our clouds were all well resolved and that random fluctuations in surface density are small on small angular scales. One interesting finding of this survey is the confirmation of previous work in the literature that most globules (and cores) are not strictly spherical but rather more elongated in shape with aspect ratios typically between 1 – 2. More interesting we find that the inner high extinction regions of globules in our sample have higher aspect ratios than their outer, low extinction envelopes. Moreover, we find a correlation between the degree of the core's departure from spherical symmetry and star forming activity within it. The central regions of globules that have stars are more elongated than those without stars. Finally we find that, similar to the cores in our Lupus 3 survey, star formation is correlated with the most massive objects in the sample. Again raising the question or whether low mass cores evolve more slowly to form stars or are relatively stable and perhaps never form stars before they are otherwise destroyed.

4)- In addition to using high resolution extinction maps to model the density structure of isolated, roughly circular cores, we have developed a similar analysis for filamentary clouds. This work involves, among other filaments, near-IR observations of the L781 filamentary cloud, which contains several clumps and an outflow at the northern edge (Figure 3). This filament has been modeled as an isothermal cylindrical cloud which is gravitationally unstable (Huard et al., in prep.). While the radius of the filament is not well constrained in this study, other physical properties, such as temperature and peak density, are well constrained given the distance to the cloud. This study also shows that, contrary to previous suggestions in the literature, isothermal models can fit the radial profiles of filamentary clouds provided such clouds can be treated as pressure-truncated isothermal cylinders.

5) With Dr. Tracy Huard, CfA, we have combined our deep near-IR observations with Spitzer mid-IR observations to derive infrared reddening laws for selected dense cores. The goal of this study is to measure the mid-infrared extinction law and investigate variations in the extinction law that might result from the dependency of dust grain composition and size on the evolutionary stage and type of environment of the core. Specifically, the study aims to (1) characterize differences between the infrared reddening law for dense cores and that for the diffuse ISM, (2) characterize differences in this law amongst dense cores, and (3) investigate whether there are differences in the law within a given core. Additionally, the results will serve as a reliable calibrator of extinction studies of cores planned by many groups using the Spitzer IRAC mid-IR detector. Initial results have been obtained for two cores (Huard et al., in prep.) and the results suggest that the mid-infrared reddening laws toward very dense and opaque cores are significantly different from that for the diffuse ISM. Furthermore, the extinction law appears to depend on density (or, column density) of the core. These changes signify changes in the dust grain population and are consistent with grain growth in denser environments. These results are currently being prepared for publication and we anticipate that a paper describing them will be submitted for publication during March 2005.

6) Papers that were published or submitted for publication during the period covered by this report:

1)- "Discovery of a Dusty Ring in the Coalsack: A Dense Core Caught in the Act of Formation?", Lada, C.J., Huard, T., Cruz, L. & Alves, J. 2004, *The Astrophysical Journal*, **610**,303.

2)- "From Dusty Filaments to Cores to Stars: An Infrared Extinction Study of the Lupus 3 Cloud", Teixeira, P., Lada, C.J. & Alves, J. 2005, *The Astrophysical Journal*, submitted January 28, 2005.

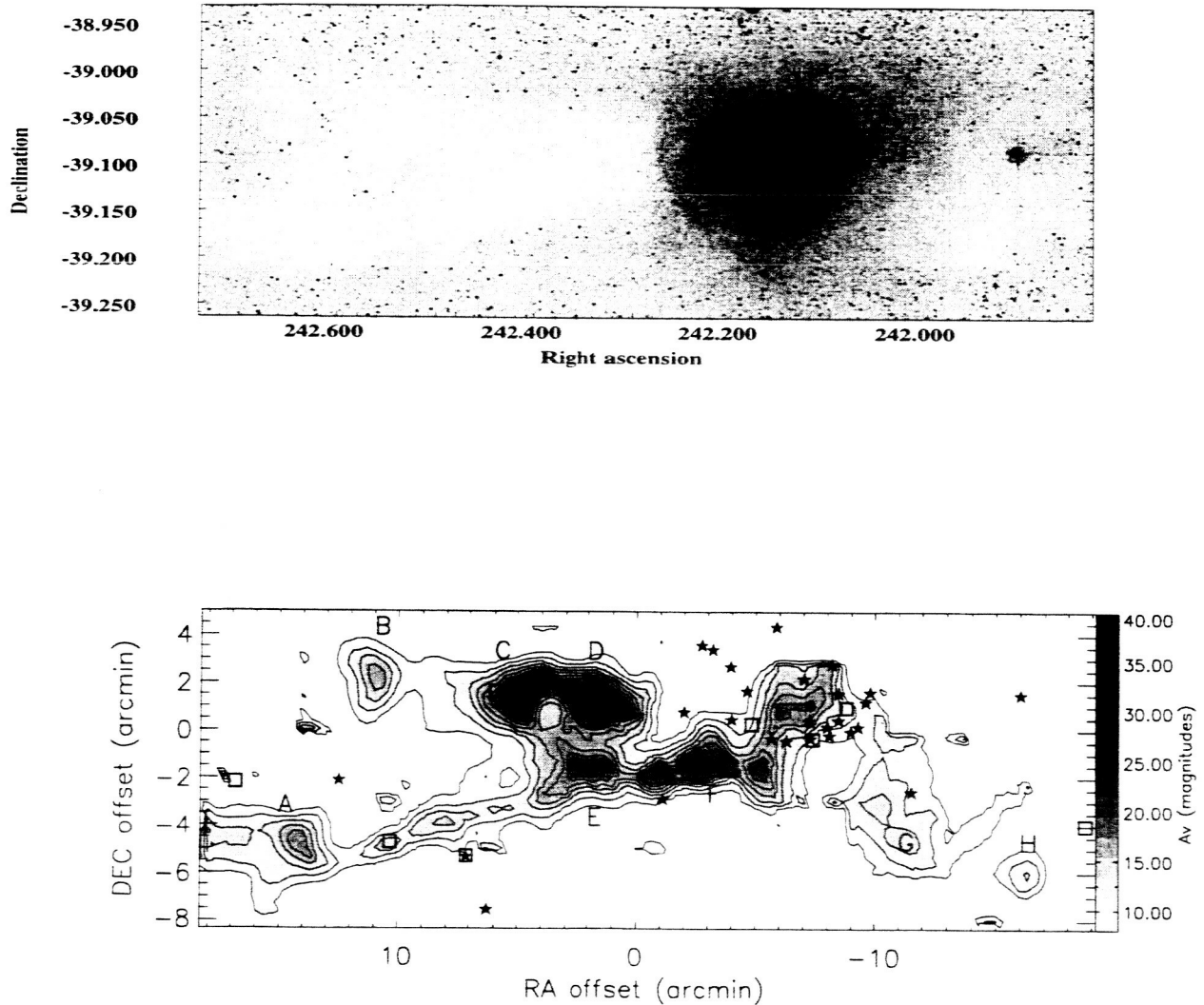


Fig. 1.— The upper panel is an optical image of the Lupus 3 molecular cloud obtained from the Digitized Sky Survey, POSS blue (inverted grayscale). The lower panel is a Nyquist sampled near-infrared dust extinction map of the same area. The JHK_s data was obtained at the ESO NTT. The extinction contours start at 8 magnitudes of visual extinction, increasing in steps of two until 20 then in steps of 5 until 40 magnitudes. The stars mark the positions of $H\alpha$ stars from Schwartz (1977) and the open boxes represent catalogued IRAS sources.

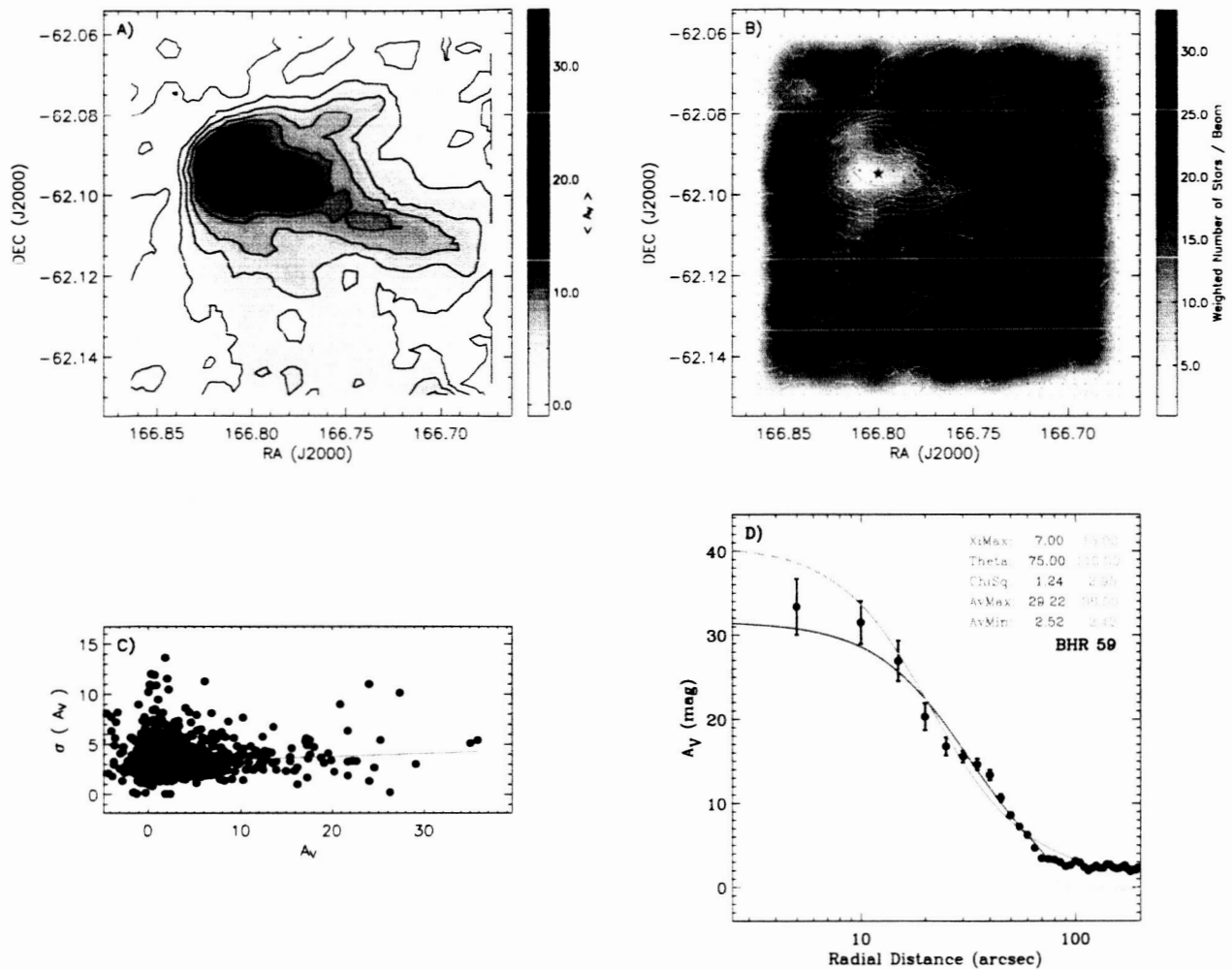


Fig. 2.— Extinction Map and Analysis of BHR 59. A) Nyquist sampled A_V map derived using the NICE method. A filled five point star marks the extinction weighted centroid of the globule used for the radial profile (panel D); B) Star count (W_V) map for sources used in panel (A) compared to the extinction contours. Counts corresponds to the sum of the radial weights applied to each star within the gaussian beam. Note, the decrease in stars per beam at the map's edge results from embedding the deep NTT data into the shallower 2MASS catalog; C) $\sigma - A_V$ relations for the extinction map. The dispersion, σ , was calculated only using stars within the FWHM of the gaussian beam. A linear least squares fit (weighted by the number of stars per beam) to the points in this plot is shown and is used to estimate an error budget for the NICE method. D) Azimuthally averaged extinction profile of the globule (solid points). The best (reduced χ^2) fit Bonnor-Ebert density profile model assuming spherical symmetry is shown (red); residuals from this fit are given as open circles. A comparison density profile (green line) is shown for either a critical or highly unstable density contrast. (green).

